Understanding Massive Black Hole Mergers:

Insights form the ASTRID / MAGICS Simulations and Implications for LISA Observations

Yihao Zhou

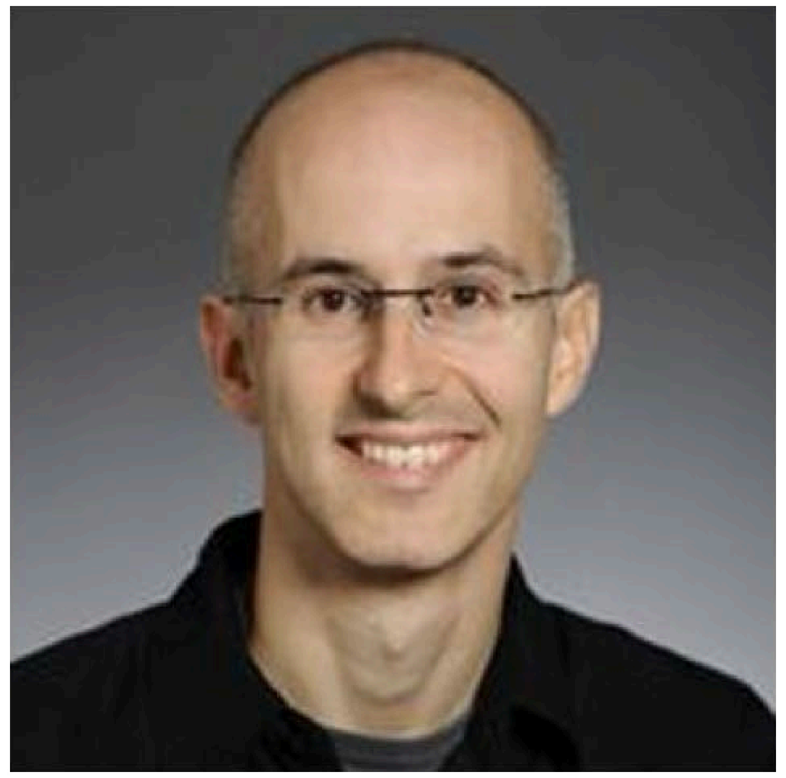
Advisor: Tiziana Di Matteo

McWilliams Center for Cosmology and Astrophysics

Carnegie Mellon University

People

Tiziana Di Matteo
(CMU)



Rupert Croft
(CMU)

Simeon Bird
(UCR)

Bonny Wang
(Master; CMU)

William Chen
(Undergrad; CMU)

Nianyi Chen
(Postdoc; IAS)

Diptajyoti Mukherjee
(PhD; CMU)

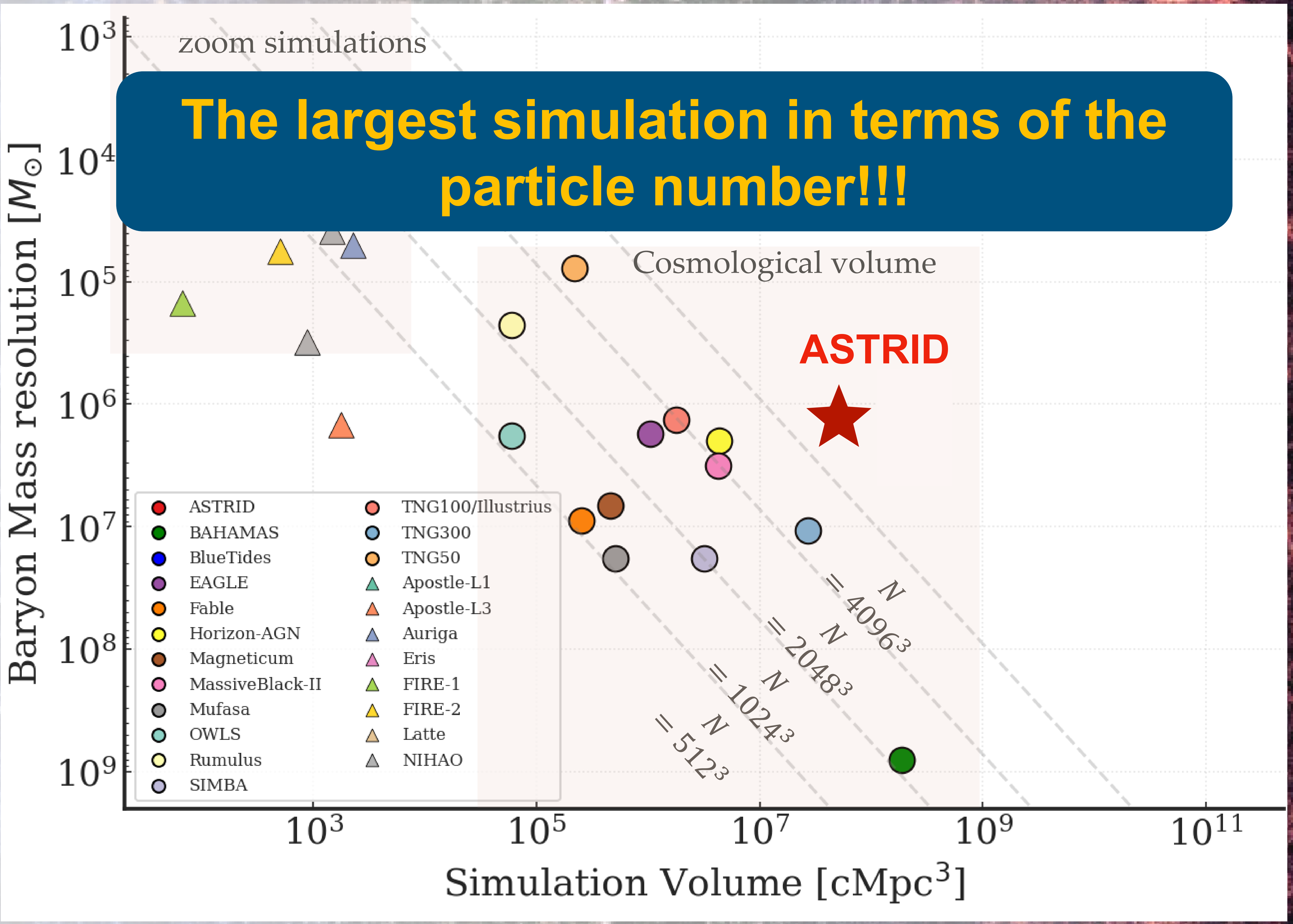
ASTRID: the largest simulation ever

Boxside: 370 Mpc

Particle number: 2×5500^3

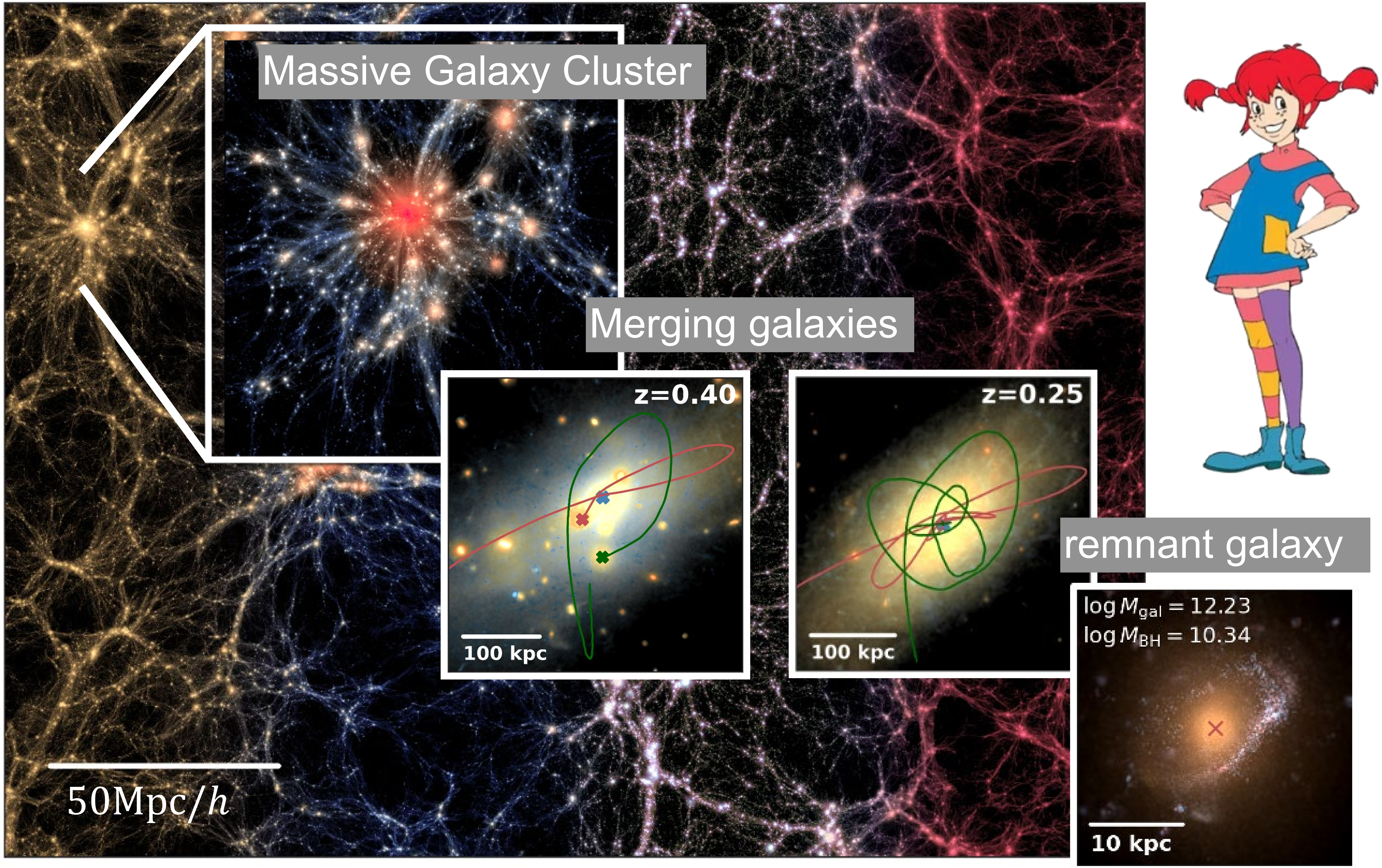
Softening length: $1.5h^{-1}$kpc

recently arrive $z = 0$



(Plot adapted from Nelson et al 2019)

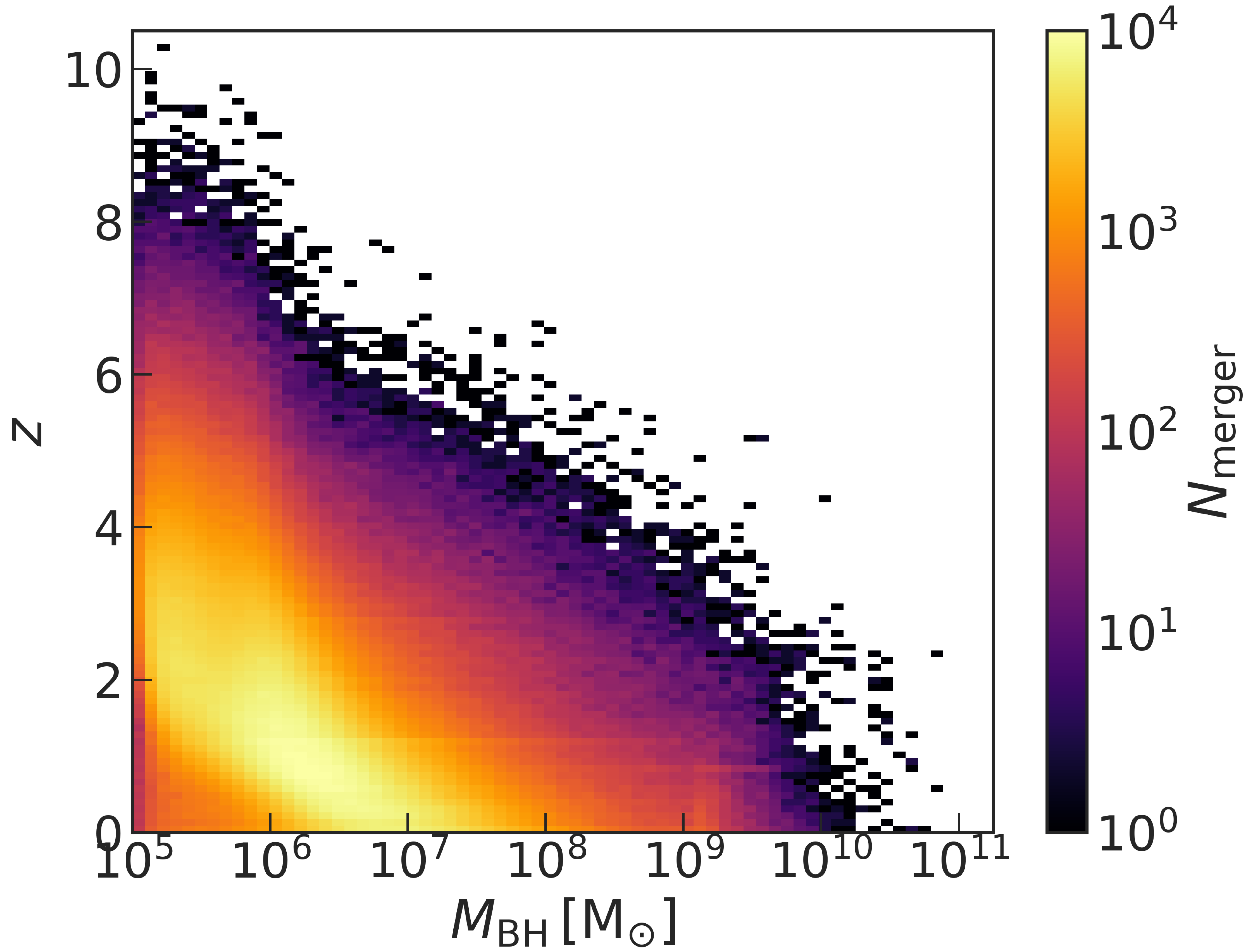
ASTRID: from Cosmic Web to Massive Black Holes



Zhou et al. 2025
arXiv:2502.01845

MBH merger population in Astrid

Over 3M mergers, covering a wide mass range: $10^5 - 10^{11}\mathrm{M}_\odot$

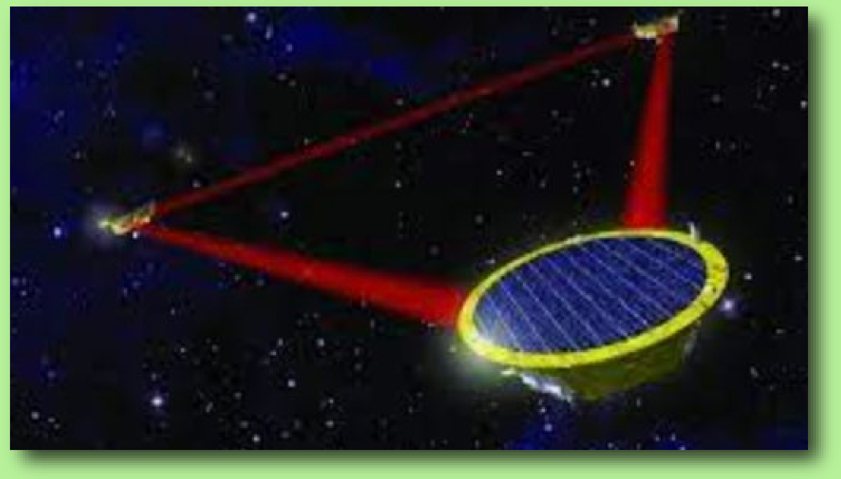


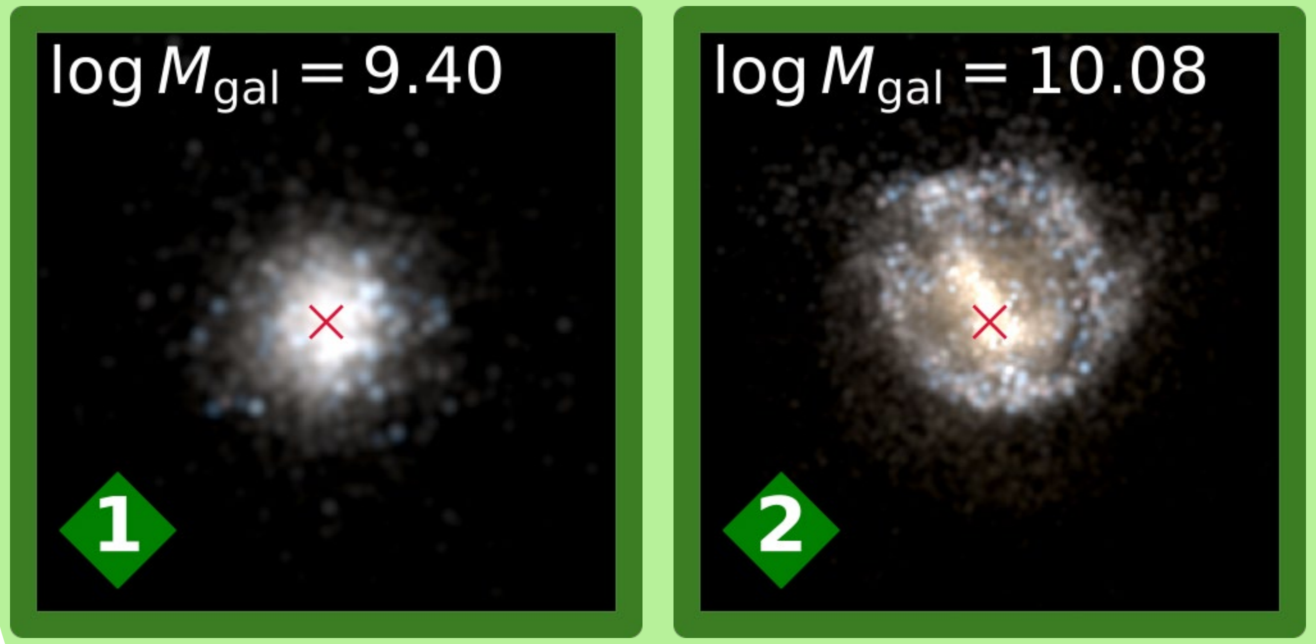
merger population in ASTRID: wide mass range

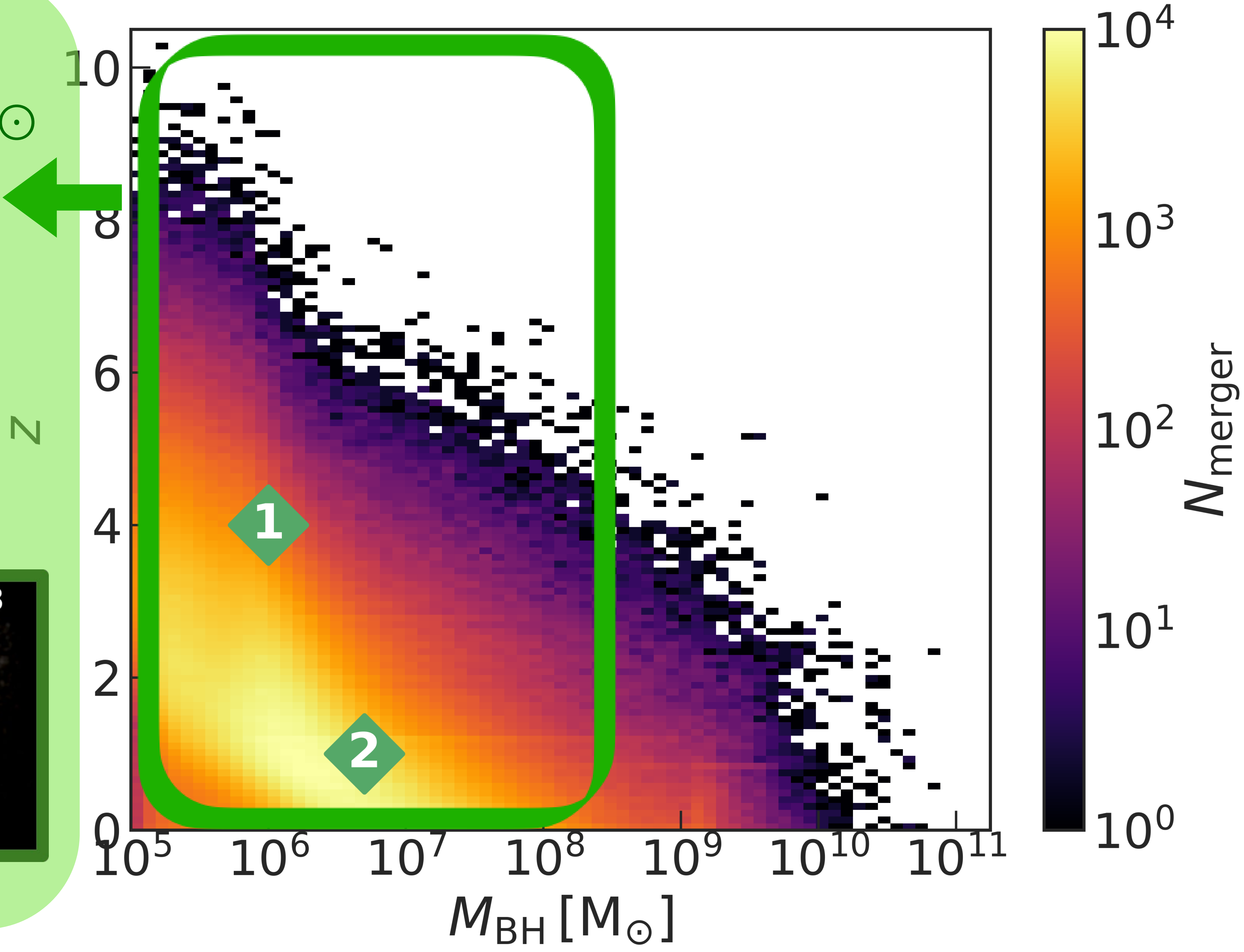
Wide mass range: $10^5 - 10^{11}\mathrm{M}_\odot$

Small MBH Seeds
Mergers down to $10^5\mathrm{M}_\odot$

LISA







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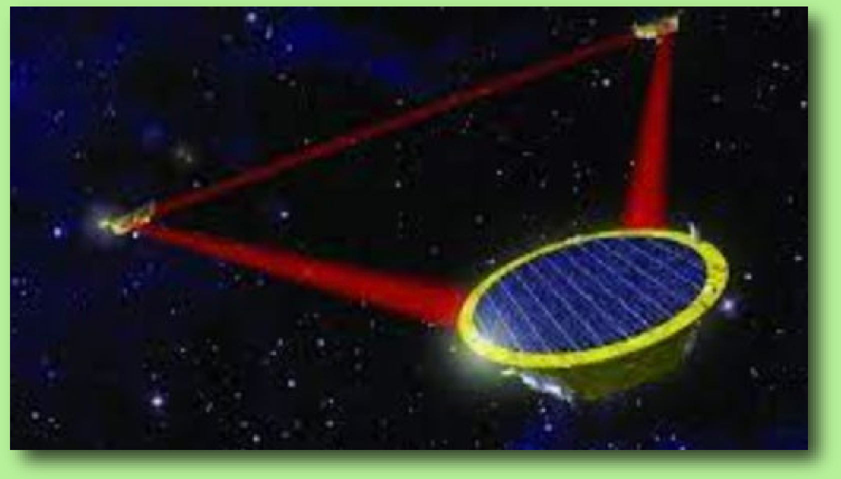
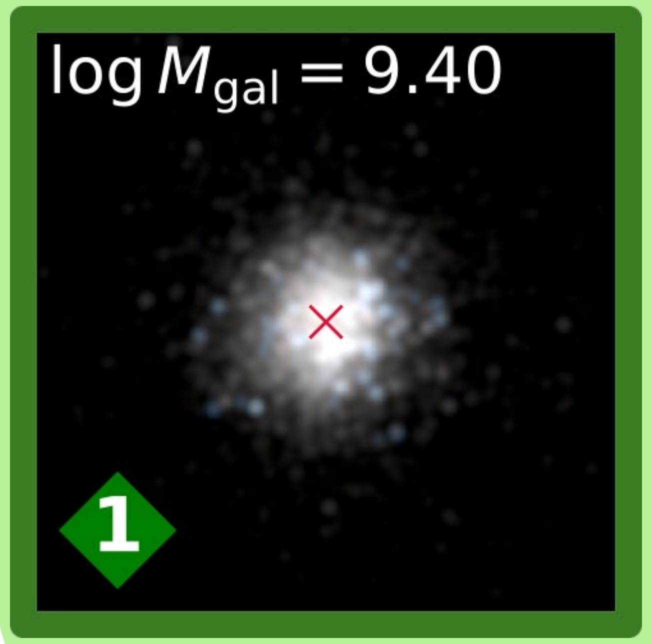
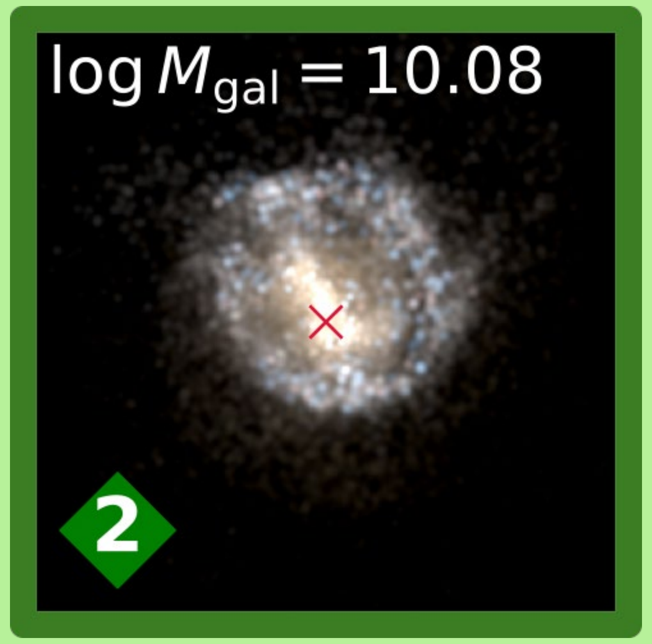
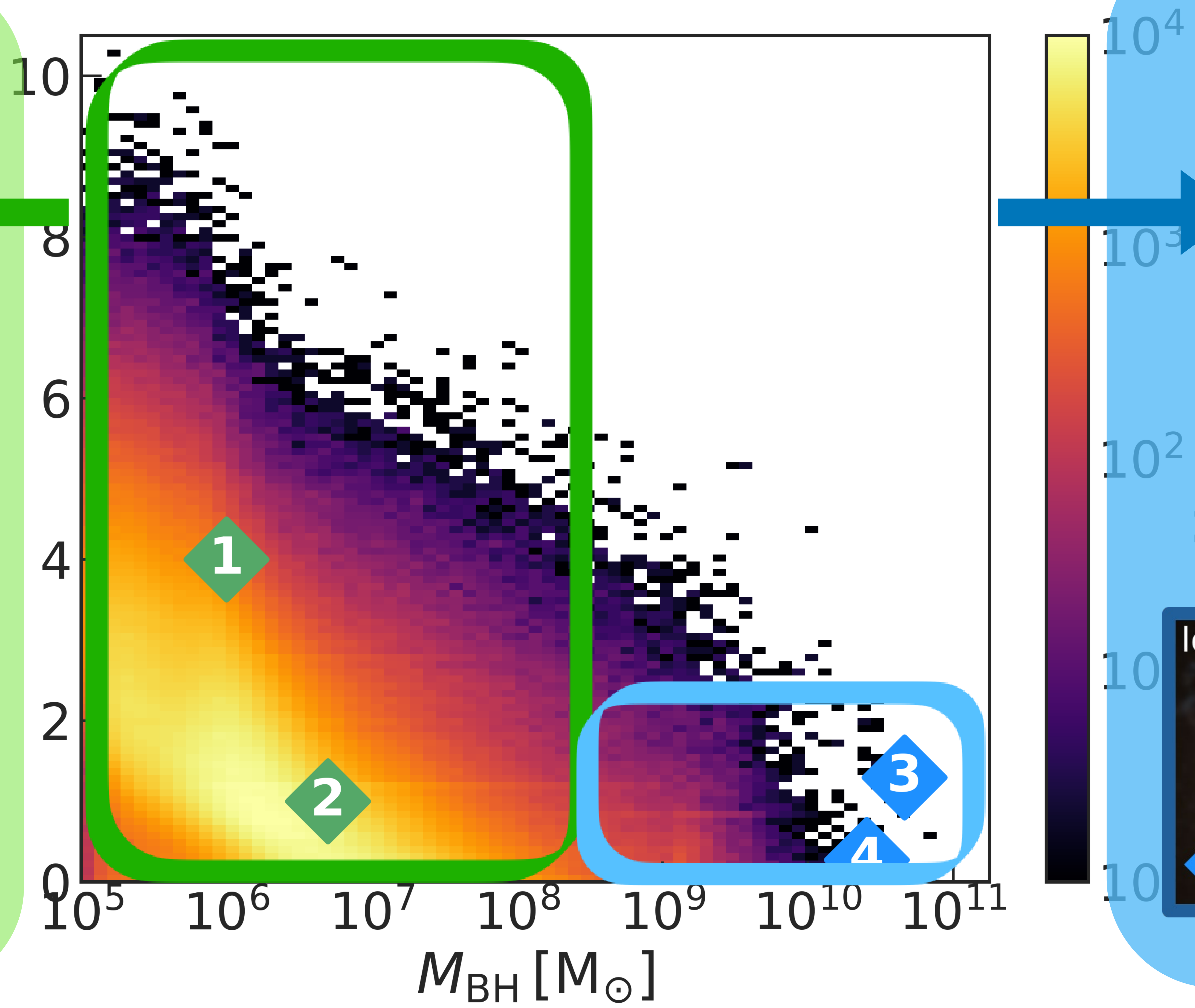




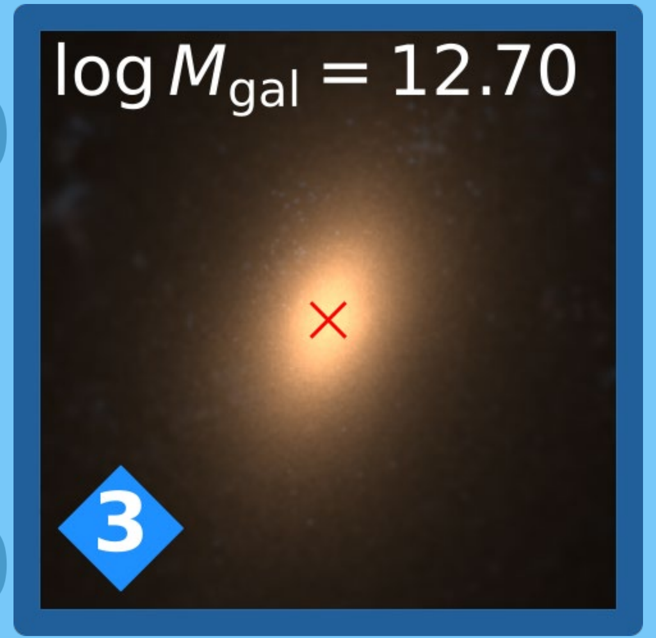


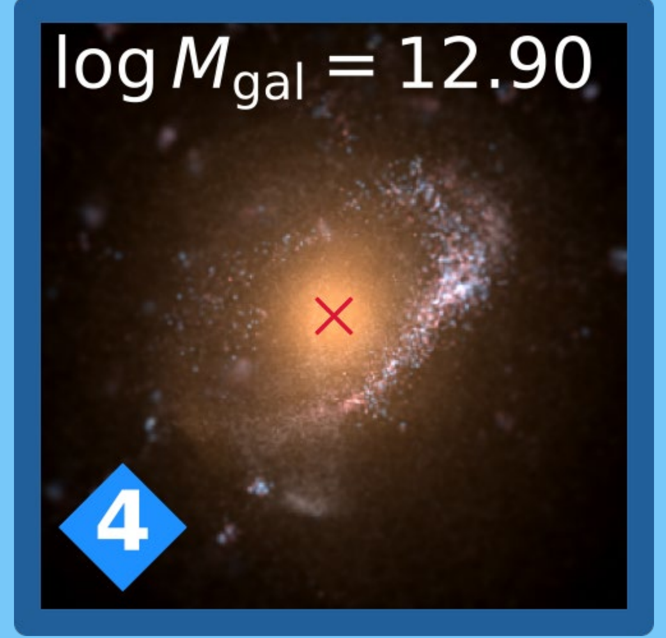


Large volume
Rare massive mergers

PTA

EPTA
PPTA
NANOGrav
InPTA
Indian Pulsar Timing Array





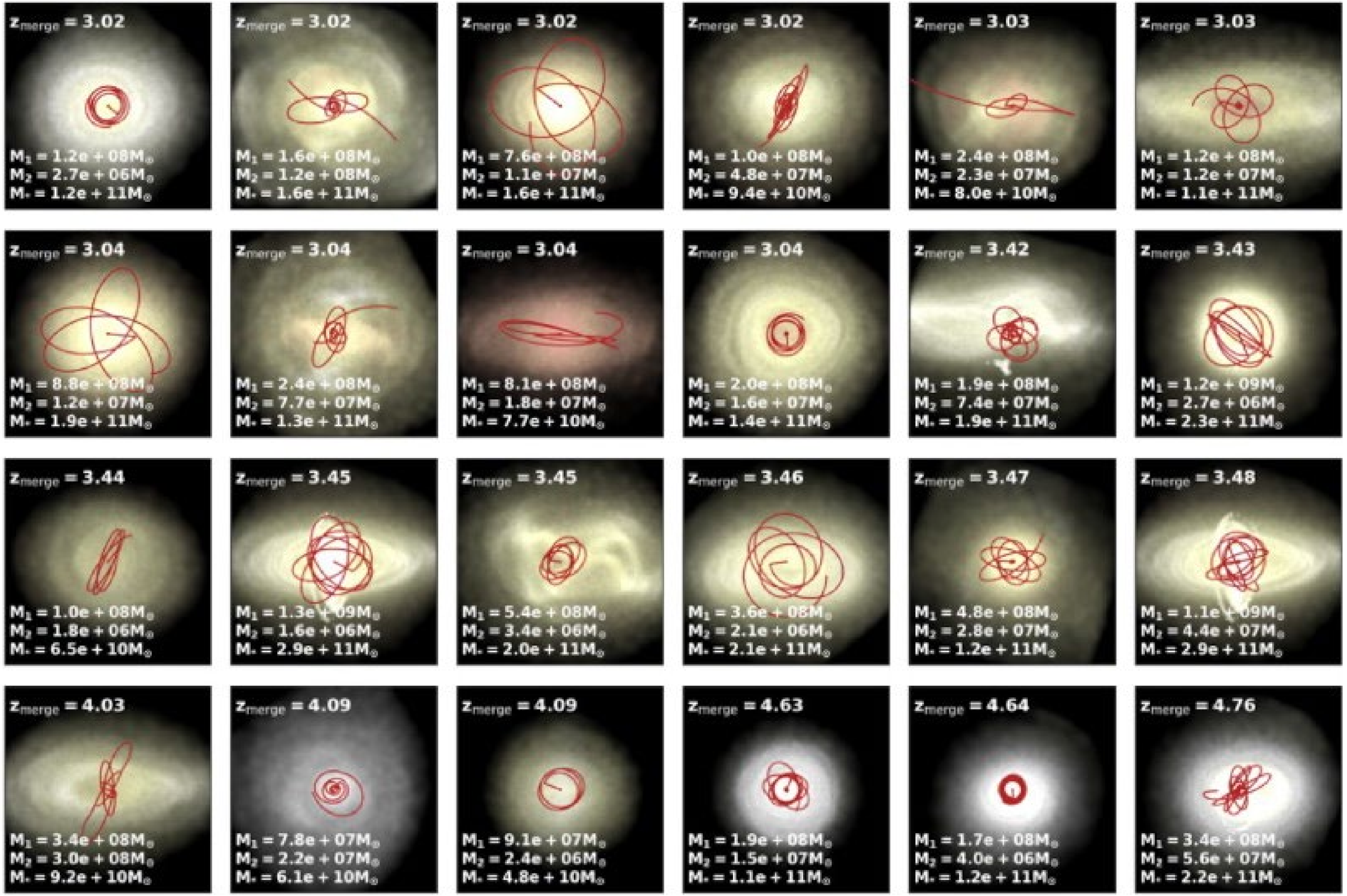

100 Mpc/h

log M_{halo} = 11.06
100 kpc
sys 1
log M_{gal} = 9.07
z_{merge} = 0.79
10 kpc
sys 1
log M_{halo} = 13.03
100 kpc
sys 4
log M_{gal} = 10.87
z_{merge} = 0.74
10 kpc
sys 4
log M_{halo} = 12.81
100 kpc
sys 5
log M_{gal} = 11.15
z_{merge} = 0.81
10 kpc
sys 5
log M_{halo} = 12.86
100 kpc
sys 3
log M_{gal} = 11.10
z_{merge} = 0.76
10 kpc
sys 3

MBH merger trajectory in ASTRID

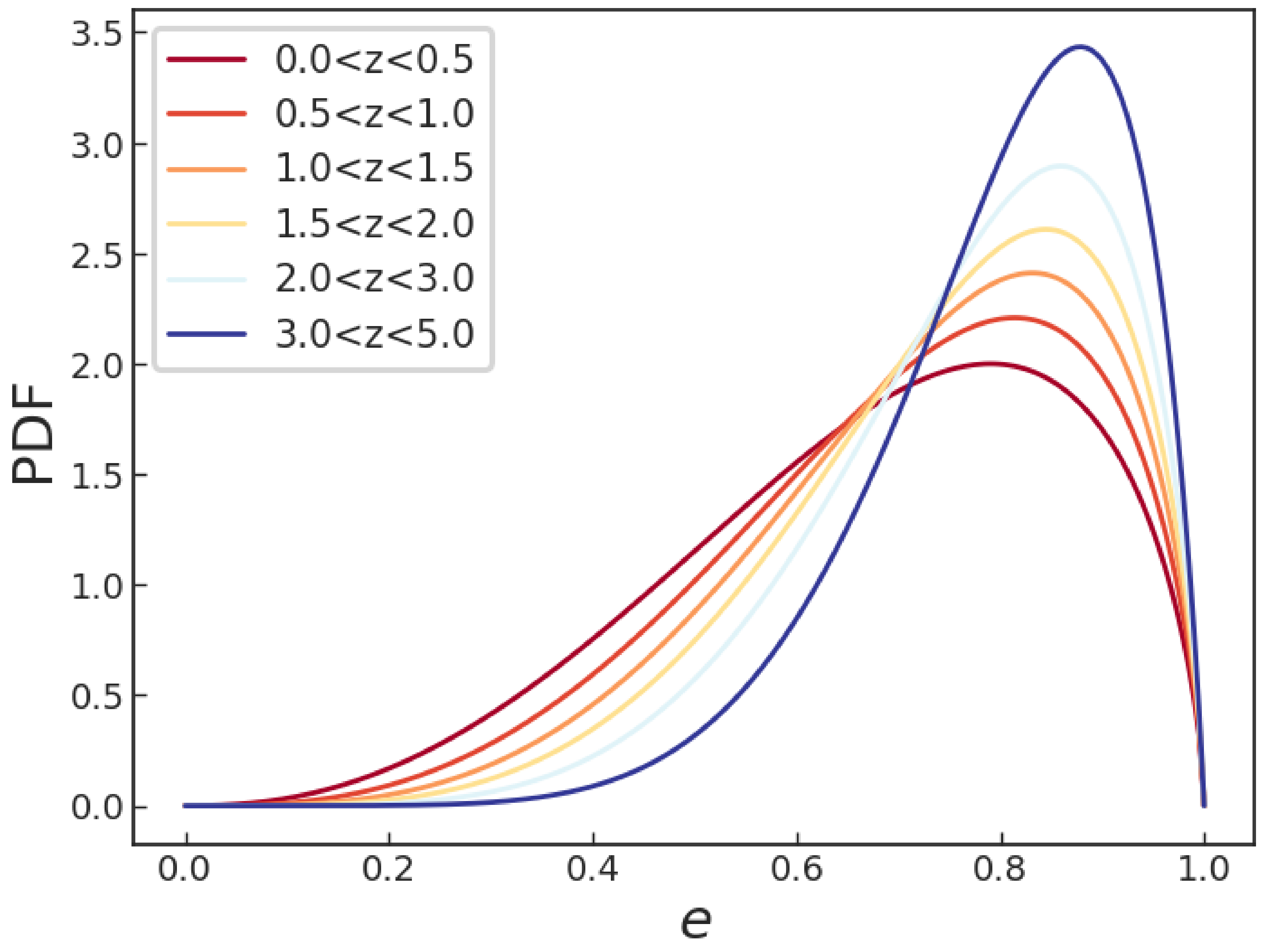
dynamical friction model —> realistic MBH merging trajectory

—> orbital eccentricity e



Chen et al. 2022 arxiv: 2112.08555

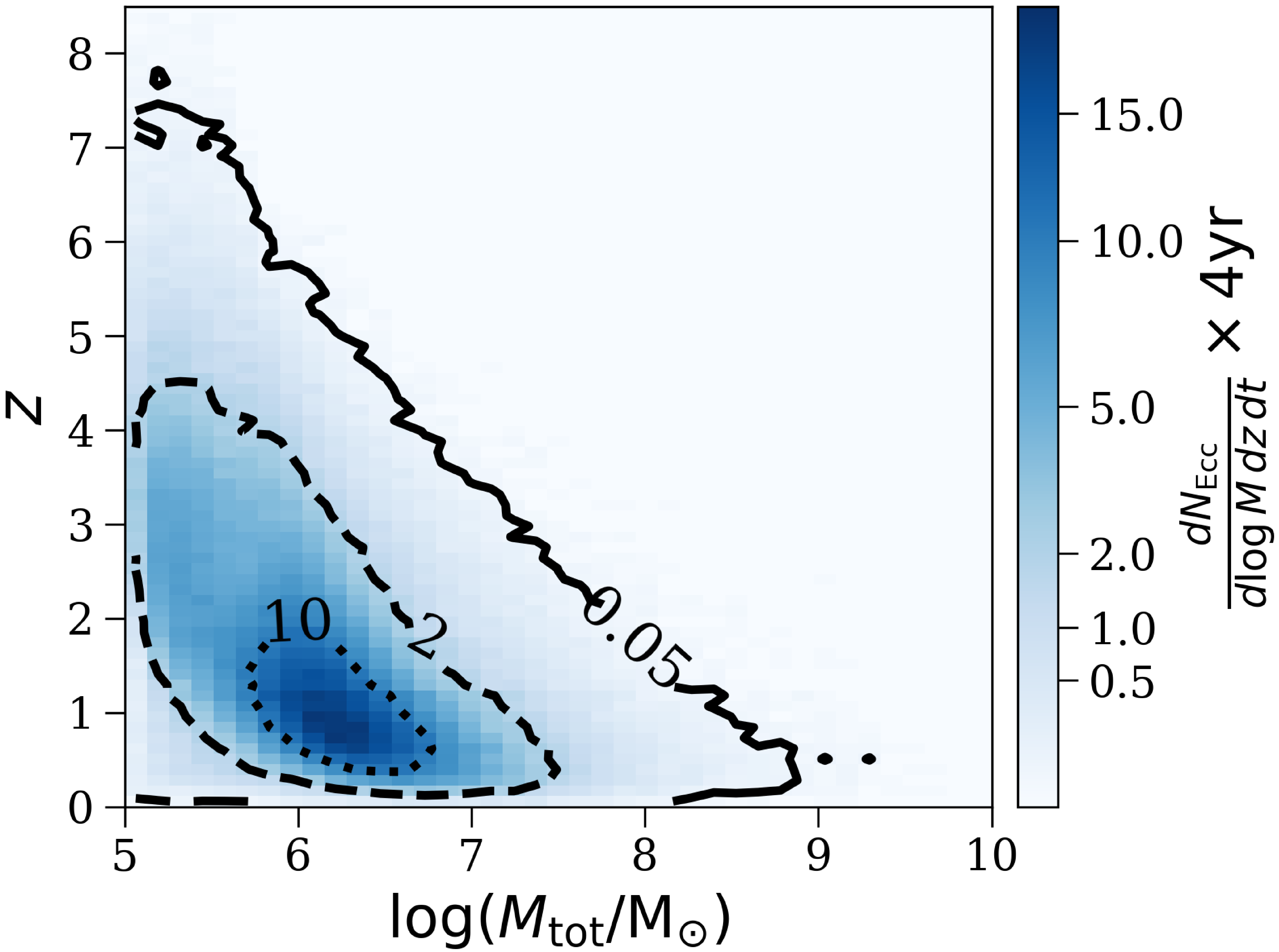
$$e = \frac{r_{\rm apo} - r_{\rm peri}}{r_{\rm apo} + r_{\rm peri}}.$$



Wang et al. 2025 arxiv: 2503.24304

LISA detection rate

- LISA detection rate is **10.5 events/yr**
- Most detected sources: mergers with $M_{\mathrm{BH}} \sim 10^6 \mathrm{M}_\odot$ at $z < 2$



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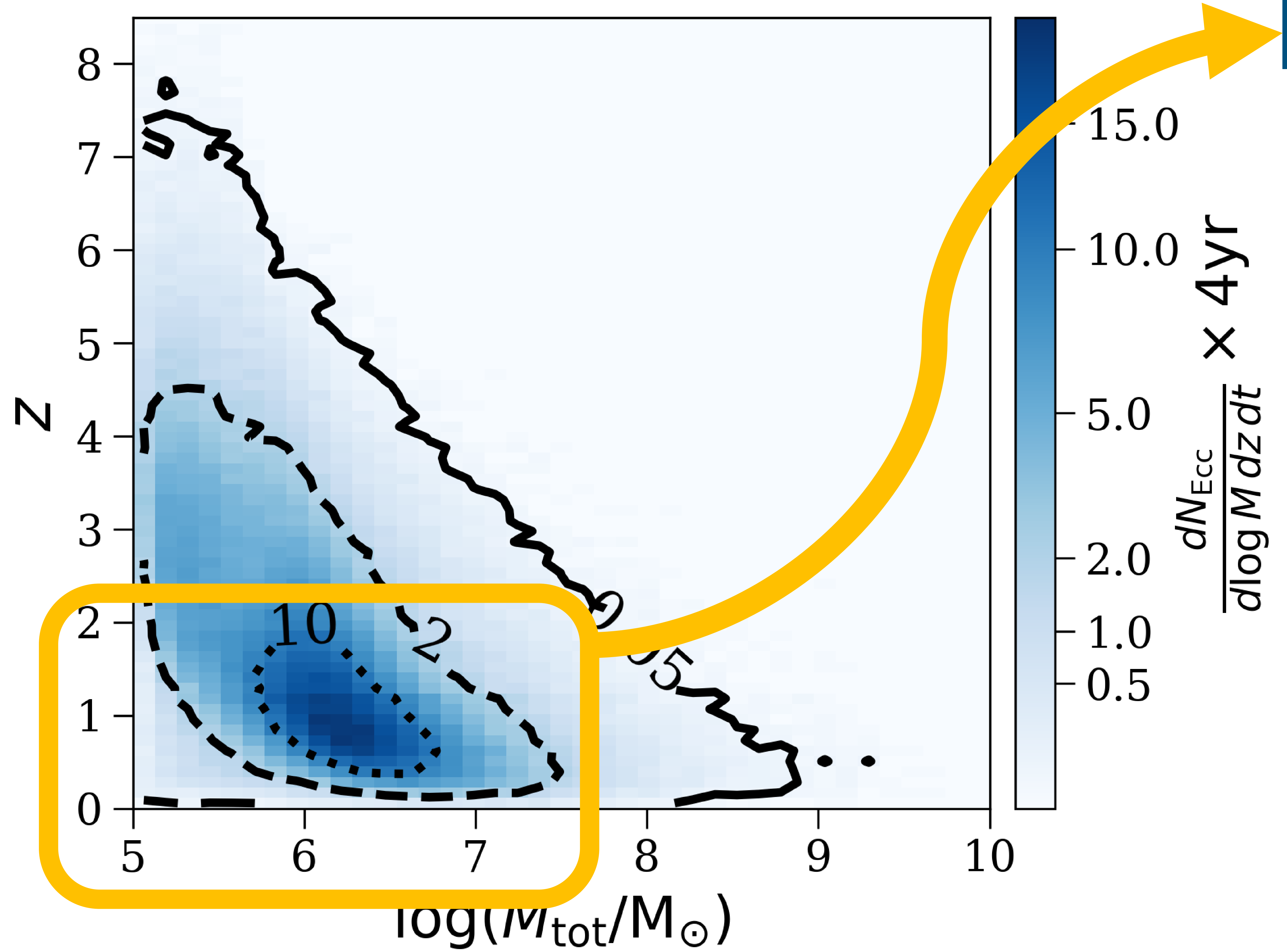
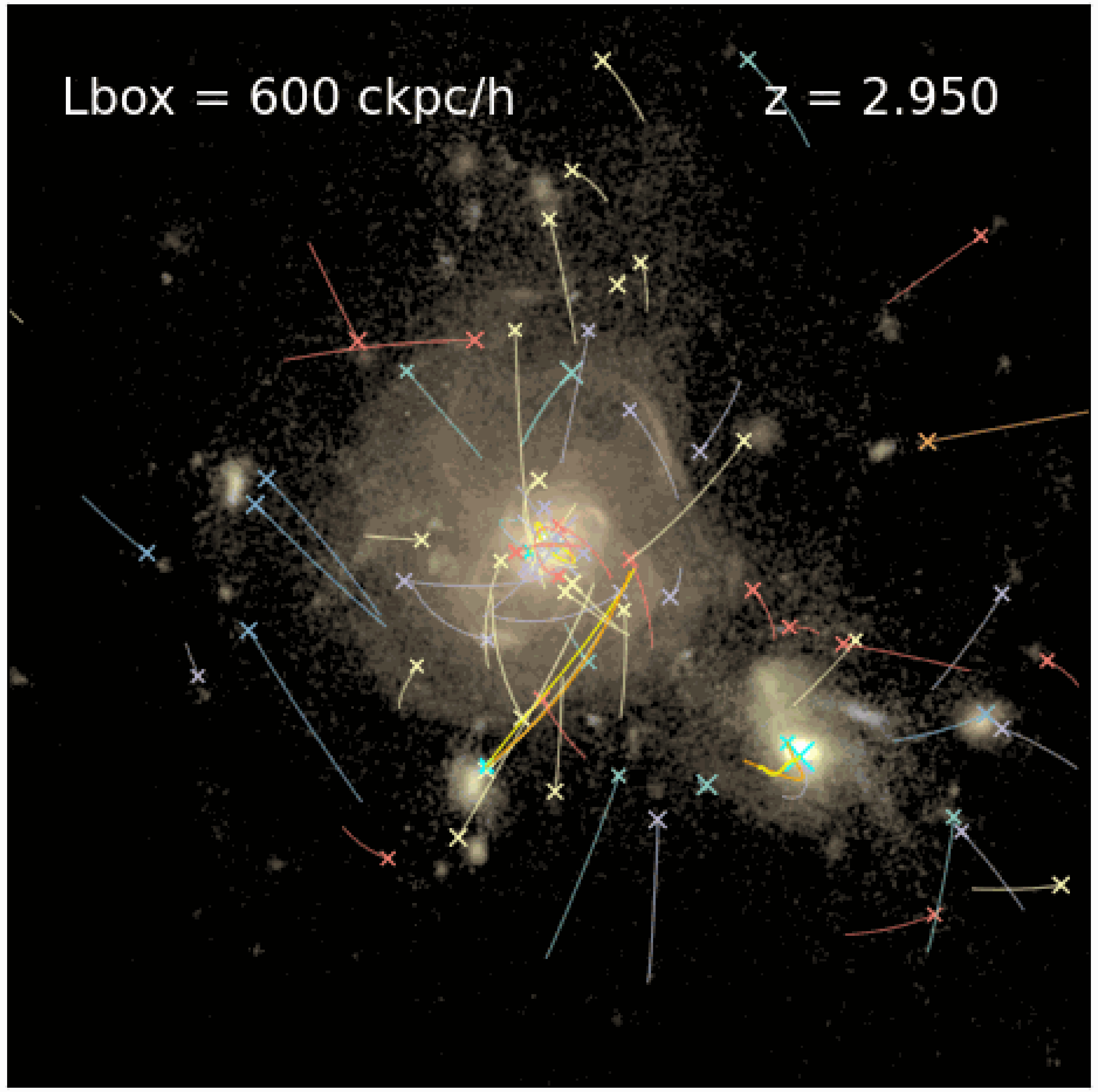


The decrease in detectability at $10^5 M_\odot$

many wandering seed MBH

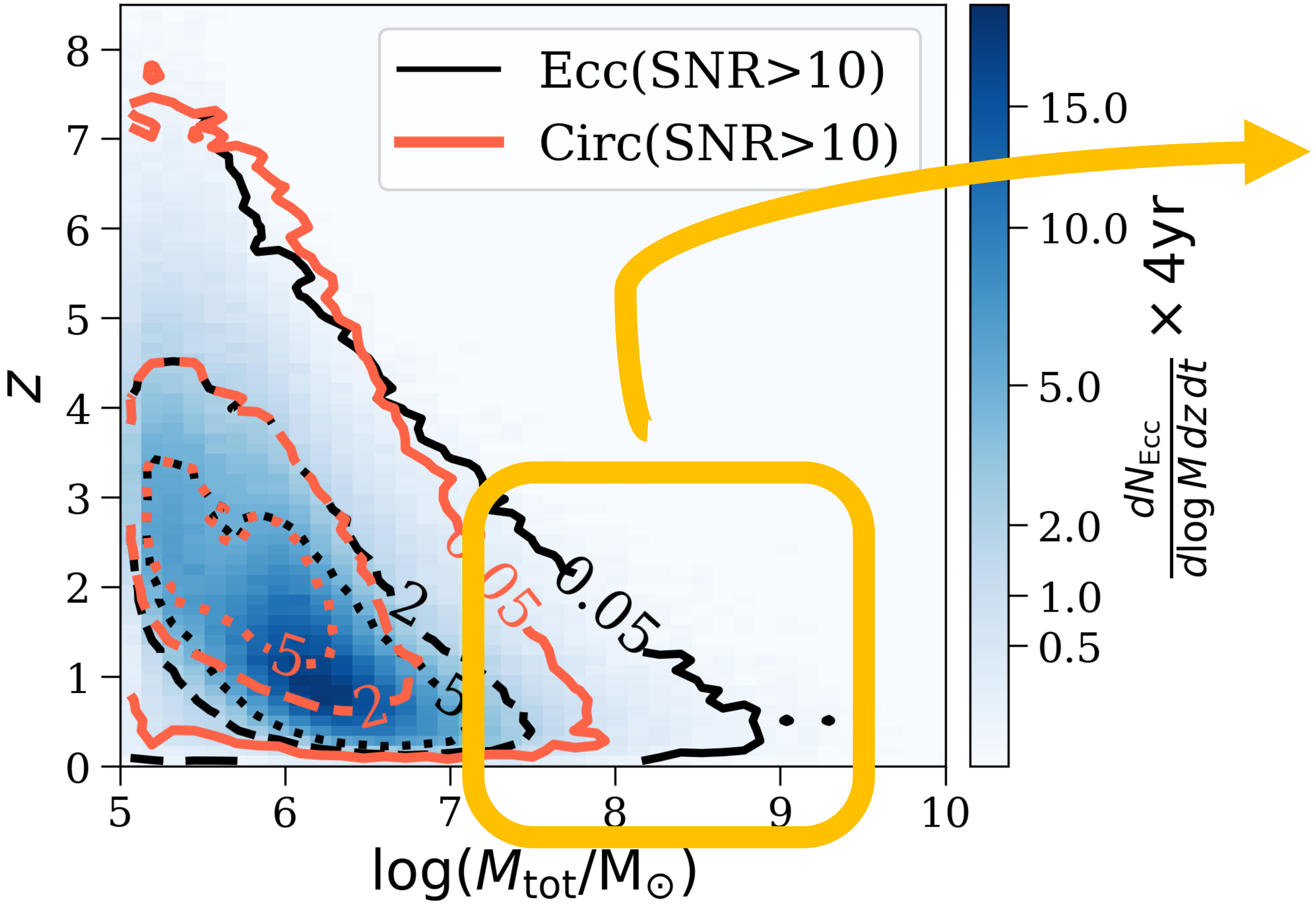


DiMatteo et al. 2022
arxiv:2210.14960

LISA detection rate: the enhancement from including e

Incorporating eccentricity enhances LISA detectability

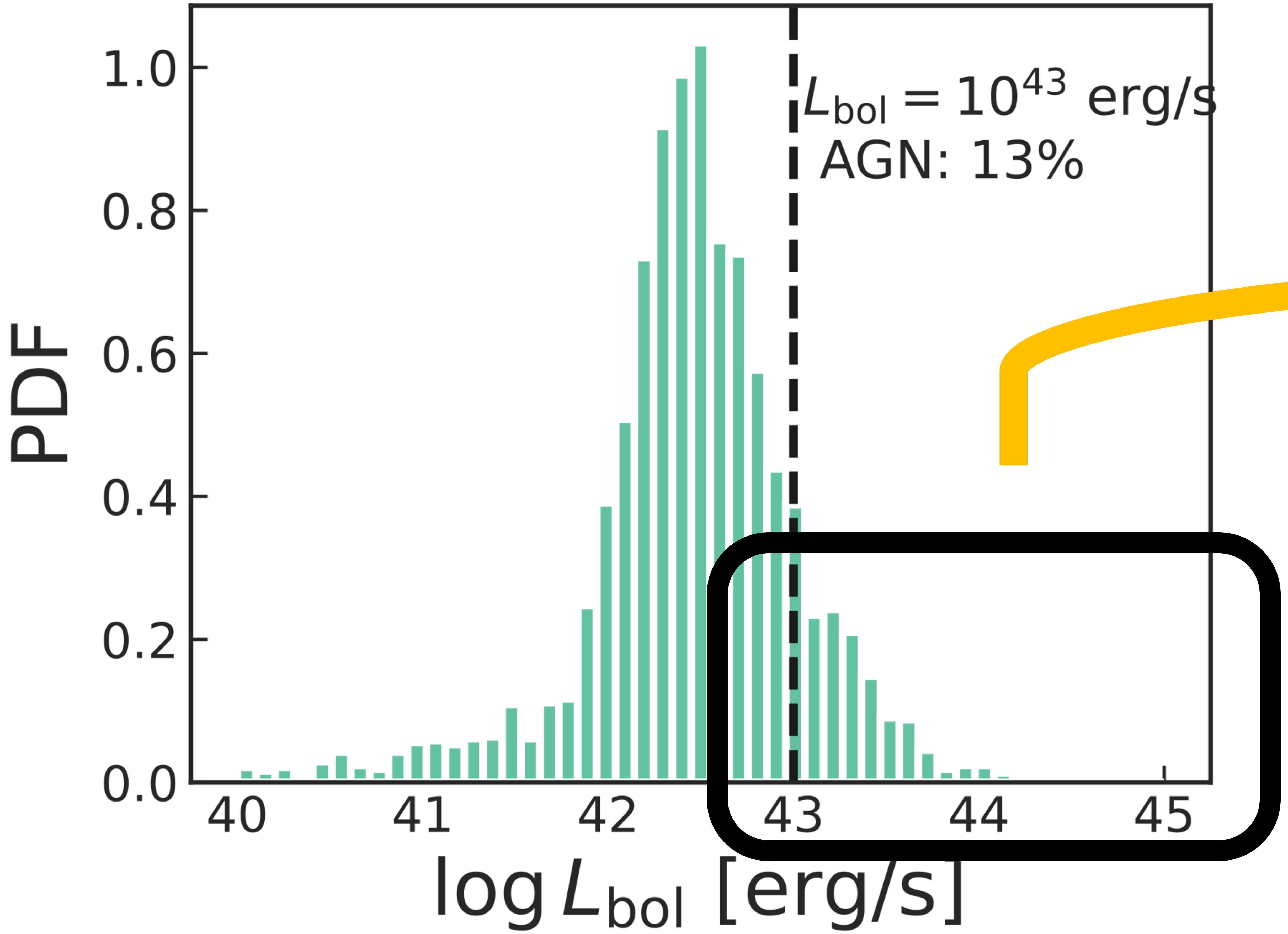
- Increasing the detected mass range **from $10^8 M_\odot$ to $10^9 M_\odot$**



Wang et al. 2025 arxiv: 2503.24304

LISA sources: low AGN fraction

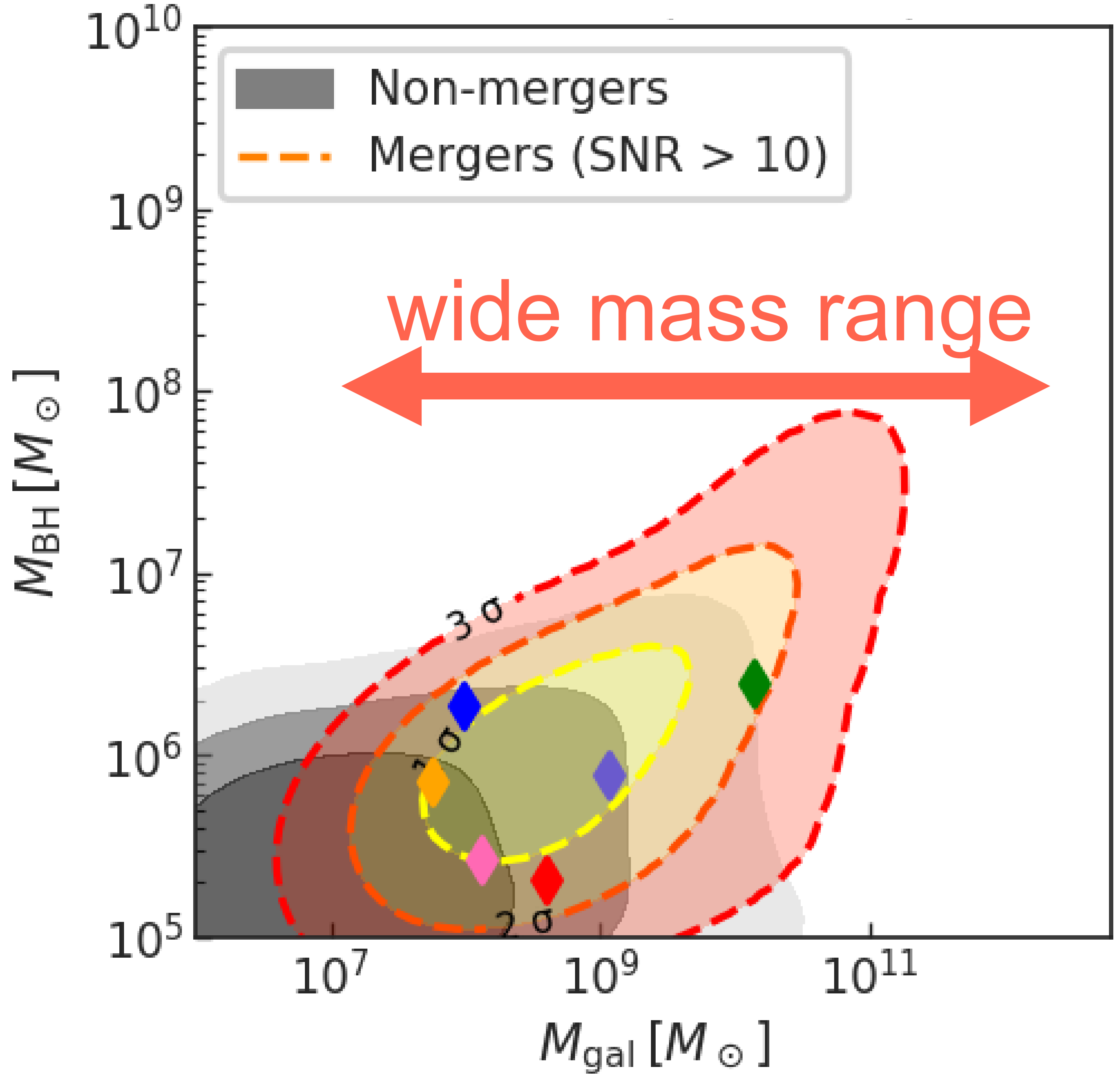
Only a small fraction (13%) of LISA sources involves AGN activity

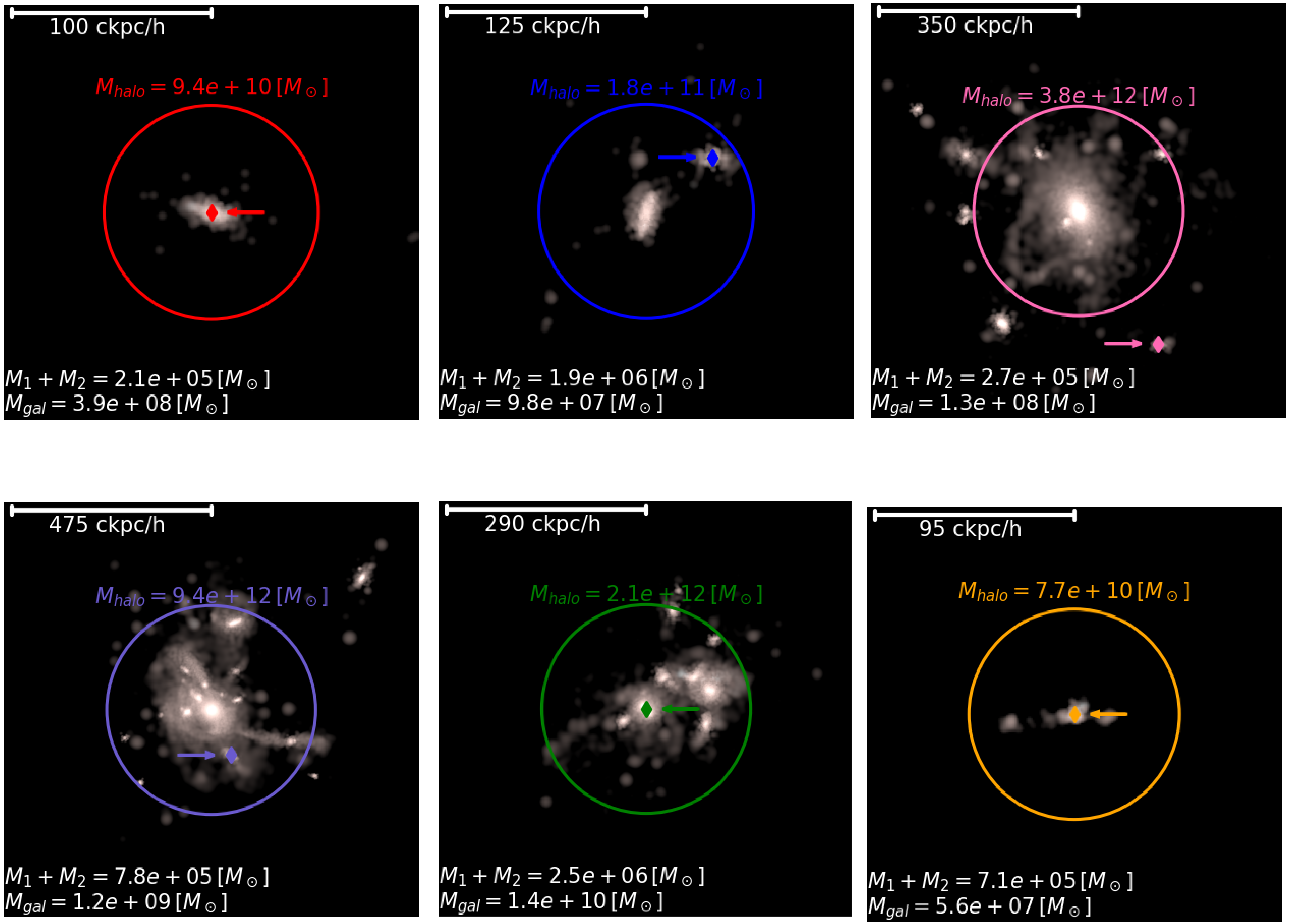


hardly likely to be Dual AGNs

Wang et al. 2025 arxiv: 2503.24304

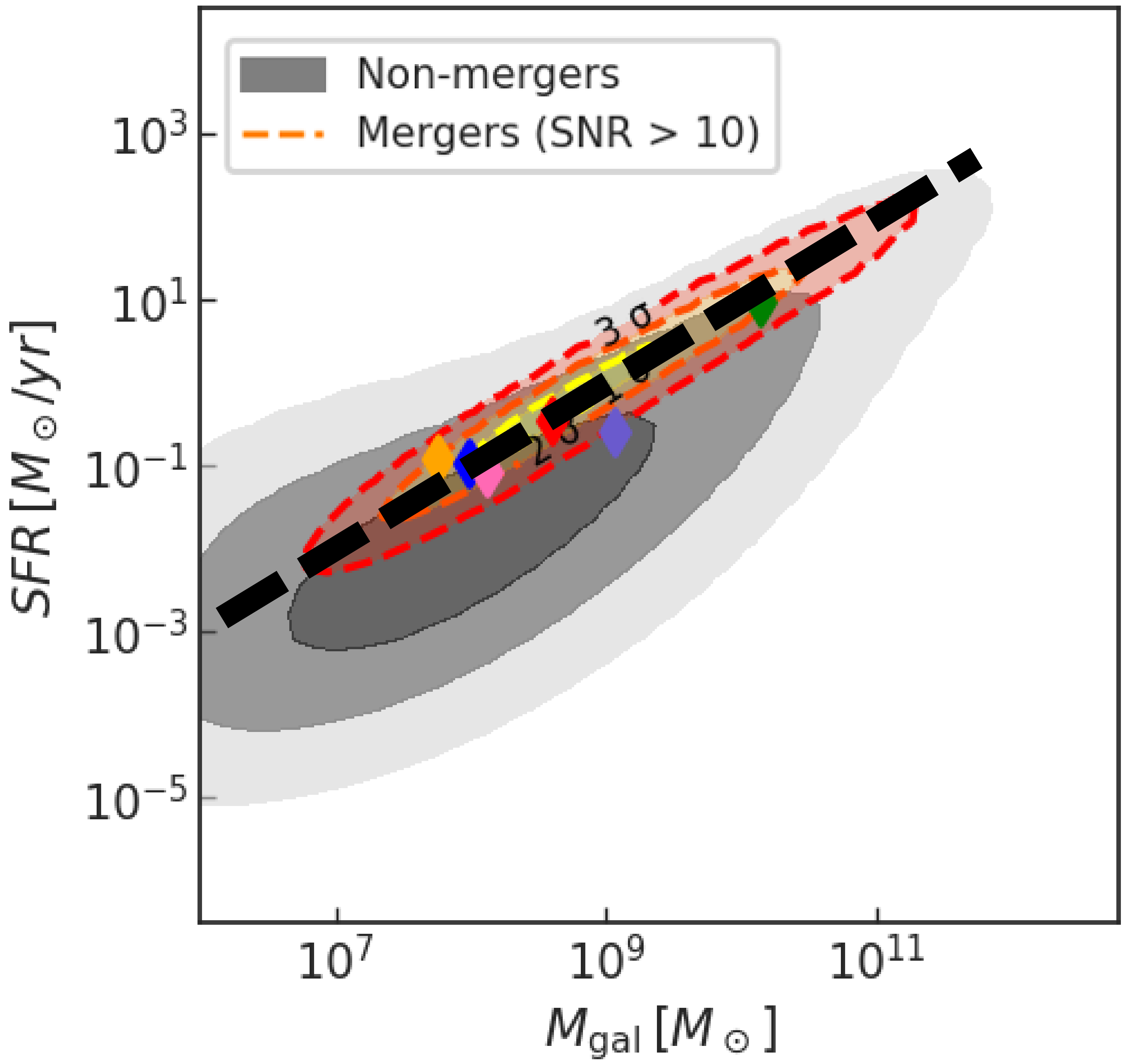
Host galaxies: low-mass ($10^9 M_\odot$) and satellite galaxies





Wang et al. 2025 arxiv: 2503.24304

Host galaxies: high star formation rate

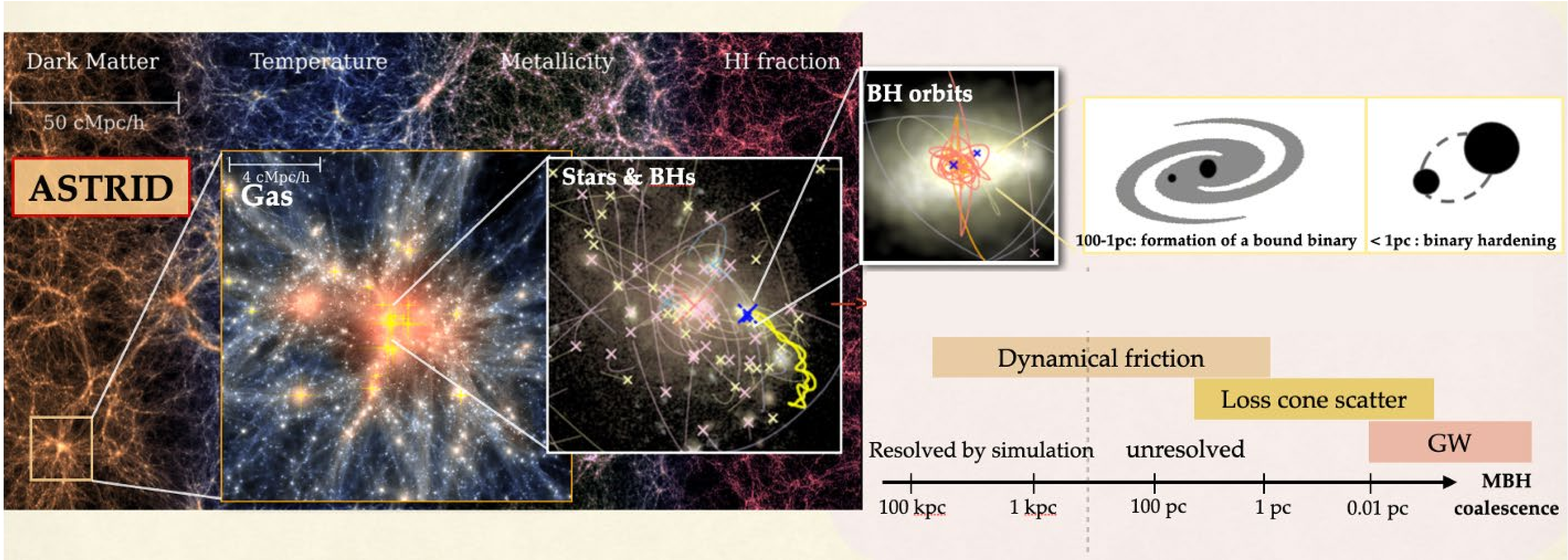


- 50% higher star formation rate
- Having a tight correlation with the galaxy stellar mass

$$\log \mathrm{SFR} = 0.9 \log M_{\rm gal} - 8$$

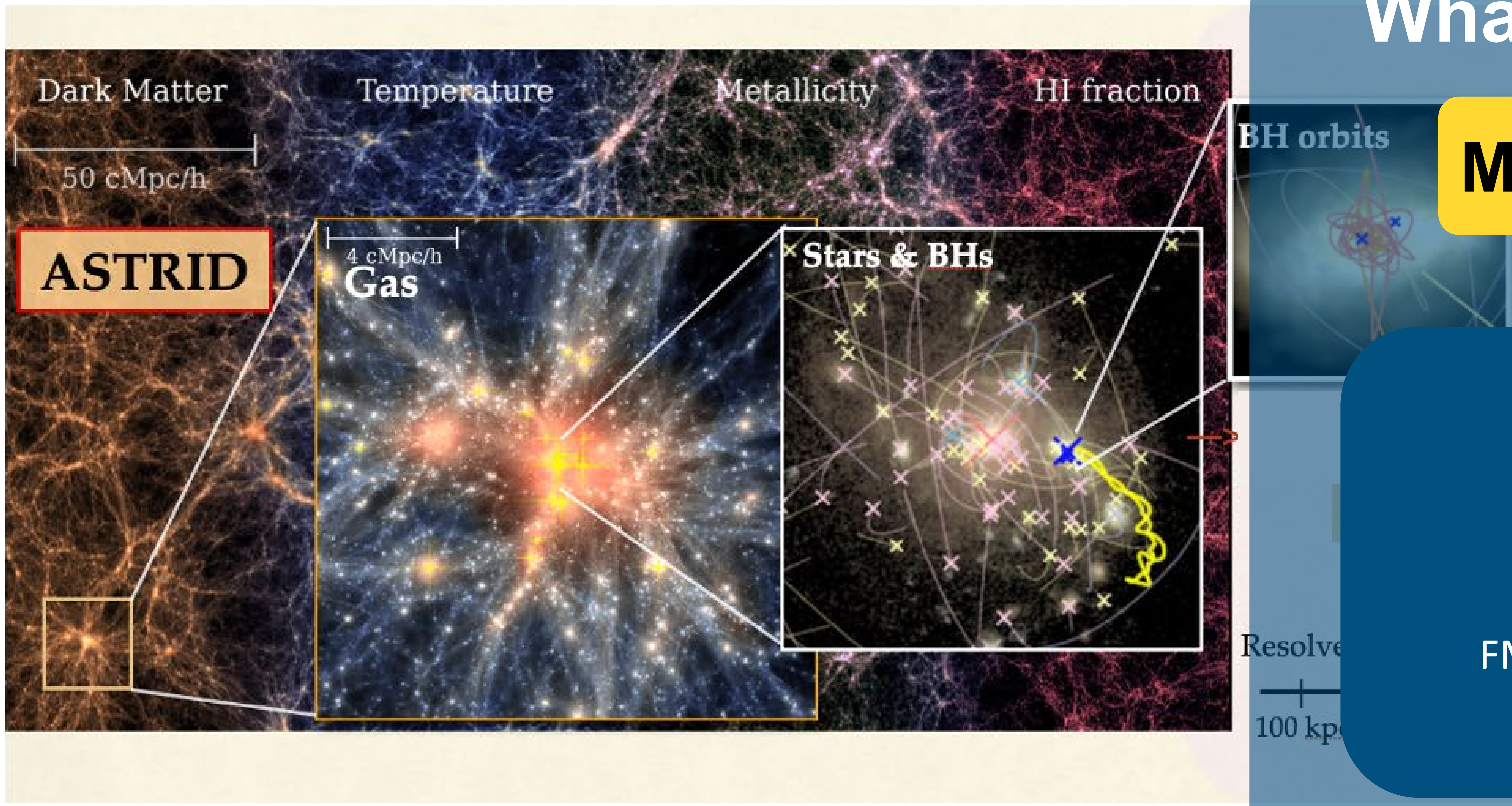
Wang et al. 2025 arxiv: 2503.24304

From ASTRID to MAGICS



ASTRID Cosmological BHs and galaxies

From ASTRID to MAGICS



ASTRID Cosmological BHs and galaxies

What happen below 1 kpc ?

MAGICS simulation suite

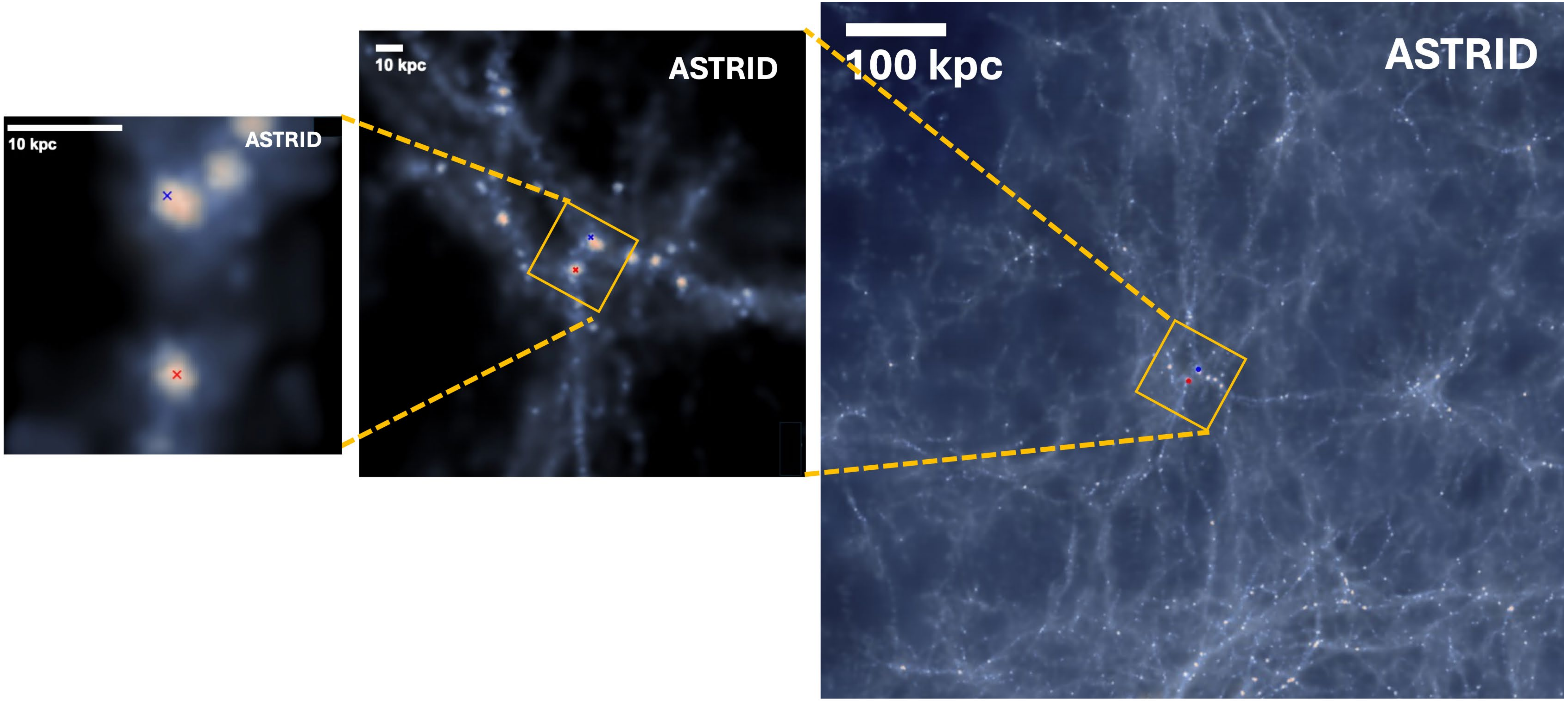
SPH code: MP-Gadget

Regularized integrator :KETJU

FMM based collisional N-body code: TAICHI

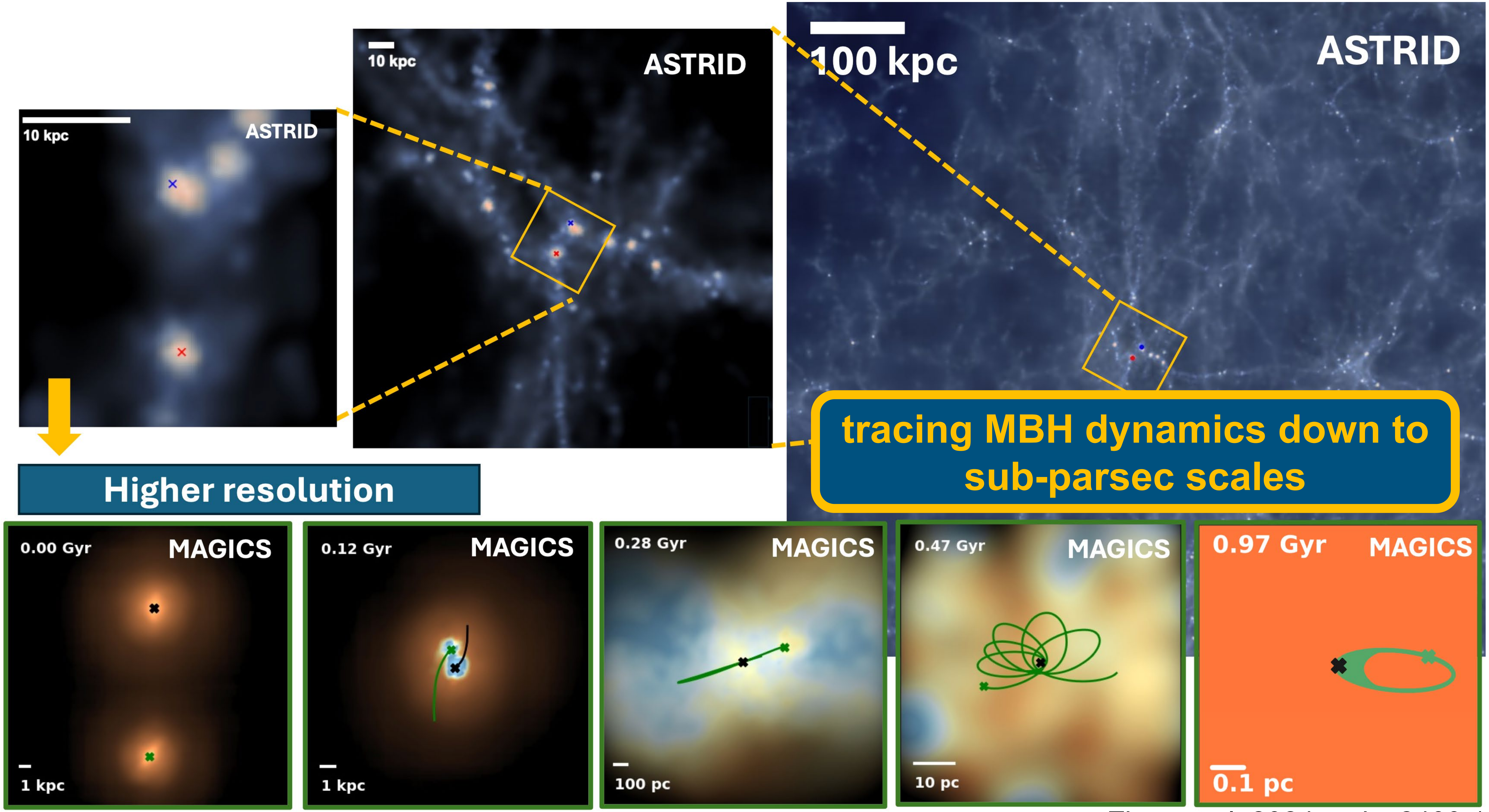
higher resolution

From ASTRID to MAGICS



Zhou et al. 2024 arxiv: 2409.19914

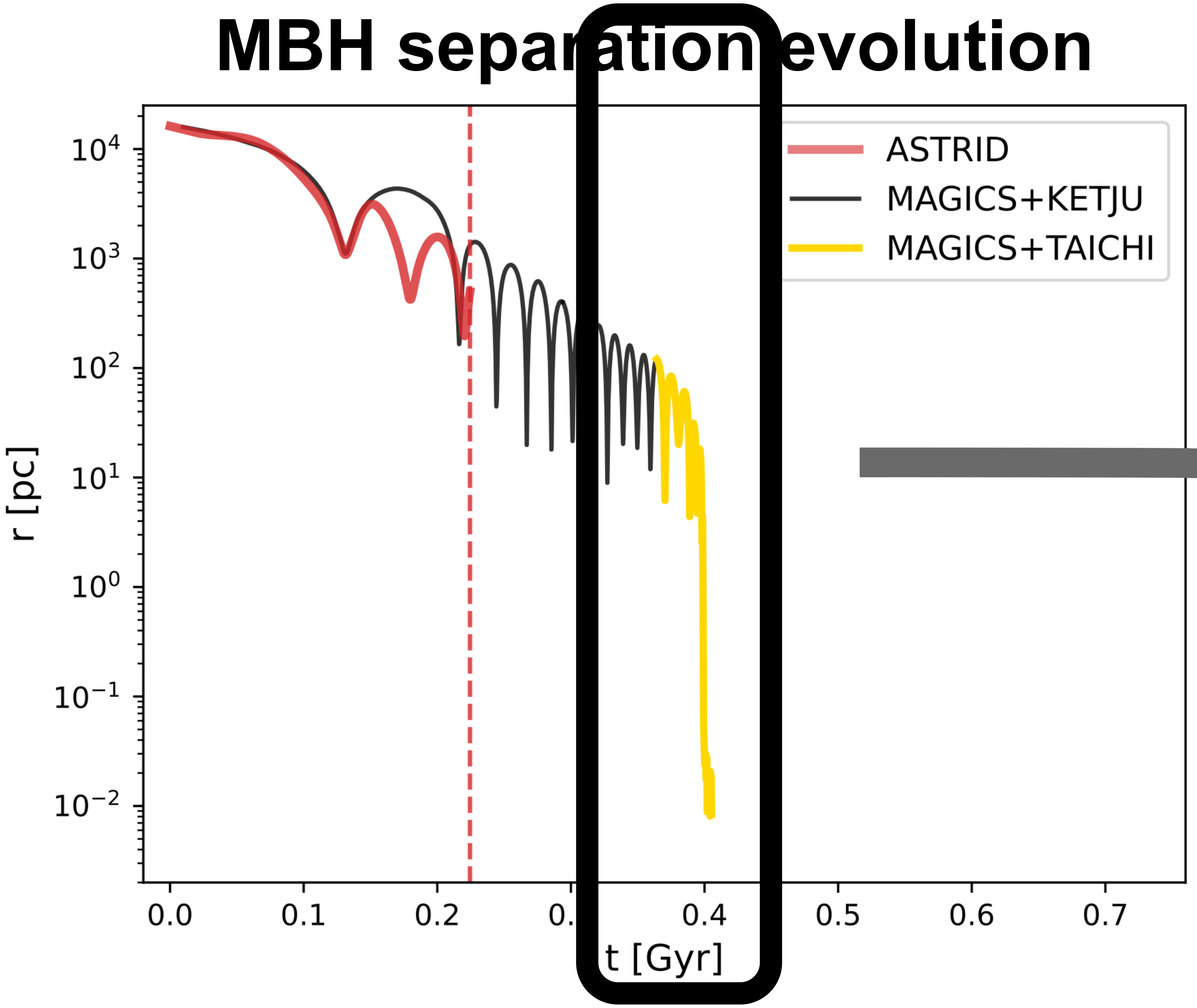
From ASTRID to MAGICS

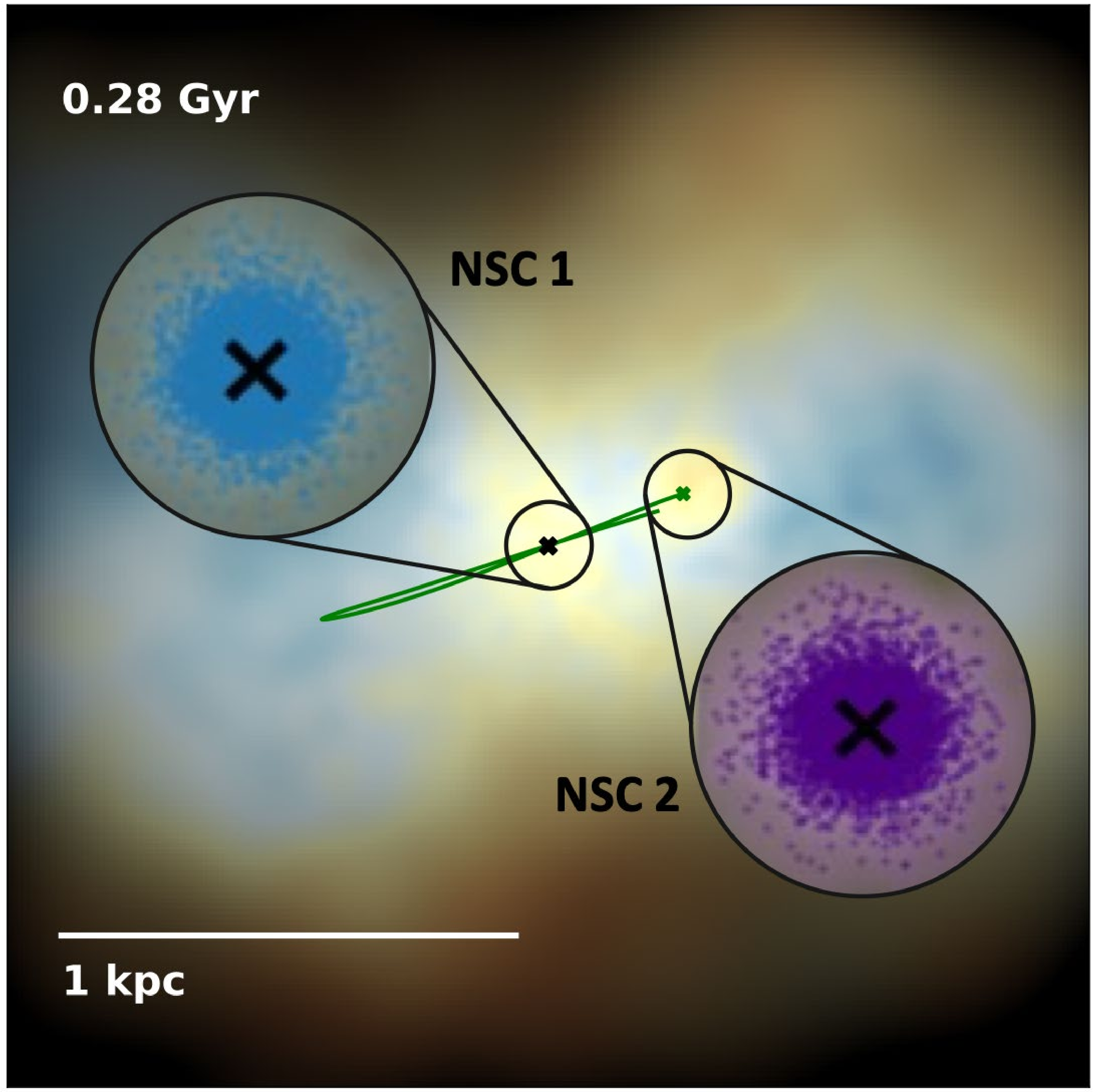


Zhou et al. 2024 arxiv: 2409.19914

MAGICS: the important role of NSC around MBH

Seed MBH in nuclear stellar clusters (NSCs) rapidly sink to the galactic center and form hard binaries!





Mukherjee et al. 2024 arxiv: 2409.19095

Conclusion

From ASTRID

- Astrid hosts a large MBH merger population, covering a wide mass range of $10^5 - 10^{11} M_\odot$
- In Astrid, MBH mergers have realistic trajectories, enabling us to measure orbital eccentricity
- Incorporating orbital eccentricity enhances LISA detectability, especially at low-redshift and high-mass end
- Host galaxies of LISA sources typically have high star formation rate, and many of them are satellite galaxies.

From MAGICS

- MAGICS simulation suite traces the binary evolution down to sub-parsec scales.
- Embedding the seed MBH within NSC accelerates the orbital decay.

ASTRID-LISA

MAGICS-I

MAGICS-II

MAGICS-III

Backup Slides

Prediction for LISA merger rate

- **Incorporating orbital eccentricity enhances the LISA detectability**
  - With circular orbits: **5.7/yr**, all merger sources
  - with orbital eccentricity: **10.5/yr**, 48 % of them (4.8/yr) are inspiral sources

Evolution of orbital eccentricity

MAGICS
ASTRID